OST TECHNICAL PROGRESS REPORT
FY 2001 RESULTS – UNSTEADY COMBUSTION TEAM

TITLE: : Unsteady Combustion Team Annual Report

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DESCRIPTION: The Unsteady Combustion Team is a part of the Gas Energy Systems Dynamics Focus Area at NETL. The primary focus of the team is to gain a better understanding of unsteady combustion phenomena and to develop sensing and control strategies to mitigate the undesirable effects of these unsteady processes. The range of activities includes modeling and simulation, laboratory-scale studies, and bench-scale investigations with sub-scale commercial hardware. Primary funding for the team has historically come from the Advanced Turbines Systems (now High Efficiency Engines and Turbines) Product Line. Additional support has also been received from the Power Systems/Advanced Research Product Line for flame studies.

There are four major project areas reported on for the year. These include: Combustion Dynamics, Sensors for Turbines, Flow Characterization and Clean Energy Systems.

Combustion Dynamics: Combustion dynamics are recognized as an industry-wide problem for gas turbine developers. Constructive feedback between the combustion and the system acoustics can produce pressure fluctuations on the order of 1 - 3% of operating pressure. Pressure oscillations of this magnitude can lead to failure of major components in a gas turbine engine, including seals, liners, nozzles and even bearings. Several research studies currently underway at NETL have focused on various aspects of this problem and have played a significant role in understanding it. The following projects examine combustion dynamics ranging from the fundamental level and extending through rig-to-engine applications:

- Rijke Flame Stability Study
- Active/Passive Fuel Injector Development
- Rig-To-Engine Project

Although the study of combustion dynamics has been ongoing for a number of years, there still exists a lack of understanding of the basic driving forces that contribute to this problem. In part, this is due to the complexity of various interactions occurring during the operation of full-scale gas turbine engines. The Rijke Flame Stability Study employs a laboratory-scale burner in an active acoustic environment. Steps are taken to reduce the influence of flow and fuel mixture variations, and a number of optical, spectroscopic, and physical measurements are combined in order to obtain a better fundamental understanding of the driving mechanisms of thermo-acoustic instabilities. Knowledge gained in the fundamental understanding of combustion dynamics can then be used to model and control instabilities in systems that are closer to real-world applications.

The control of thermo-acoustic instabilities is investigated in the Active/Passive Fuel Injector Development Project. This study builds on the concept that pressure oscillations are driven by phase matching between variations in the heat release and acoustic pressure by evaluating the damping capability of varying acoustic response, or impedance, of a fuel injector on combustion dynamics. Adjustment of the acoustic impedance of the fuel system using a variable geometry resonator can change the phase of the fuel delivery. This adjustment can accommodate changes in the combustion response that occur with engine load or operation. The theoretical behavior is similar to active control, but without the sensors or actuators. The actual behavior depends on the level of dynamic response that can be achieved in practical fuel delivery systems.

Even with an understanding of how instabilities occur and are driven and the application of proven control strategies, experience has shown that full-scale engines sometimes exhibit strong instabilities. These rig-to-engine variations can occur due to changes in the flame shape or structure brought on by unforeseen component interactions. These changes in the flame are difficult to predict and measure at realistic gas turbine conditions. The Rig-To-Engine Project is focused on experimentally measuring how the flame responds to external perturbations. This information may be useful in identifying potential problems early in the development cycle. This capability could pay huge dividends for all gas turbine manufacturers, but the in-situ measurement is complicated by the harsh environment and requires some effort to refine.

Sensors for Turbines: Serious engine damage can result in lean premixed combustion systems when flames flashback into the nozzle. Currently there are no methods to sense when flashback may be incipient. Related problems can arise from autoignition, where fuel begins to burn in the premixer without any flashback. Because of the presence of heavy hydrocarbons or pipeline cleaning solvents in natural gas, the operating margin for autoigntion may be compromised in high-pressure gas turbines. Likewise, operation near lean blowoff is desired to reduce NO_X emissions, but this complicates the change to different fuels, because the flame anchoring may be different with different fuels near the lean blowout limit.

Because of these issues, it is desirable for advanced combustion systems to include localized sensing of combustion parameters for improved reliability, availability, and maintainability. Additionally, such control may enable additional reductions in fielded NO_X levels, without the need for after-treatment systems like selective catalytic reduction (SCR).

The goal of this project is the development of durable low-cost in-situ monitoring techniques for gas turbine combustion systems. The technique employed is based on the flow of electrical current through a hydrocarbon flame that results when an electric field is applied across the flame. Hydrocarbon flames are good conductors of electrical current, and the electric current through the flame relates to the amount of hydrocarbons consumed. Furthermore, sensors under development in this program will also benefit future integrated gasification combined cycle (IGCC) power plants, as well as DOE initiatives in fuel-flexible combustion systems.

Flow Characterization: Development of low-emission combustion systems depends on understanding the mixing processes in the fuel/air premixer and in the combustor. For example, some catalytic combustion systems require premixing levels to within 10% standard deviation to avoid damaging the catalyst. This level of premixing is difficult to achieve in the mixing lengths available in the usual flow path between compressor and combustor – the problem is exacerbated by the relatively low-speed flow that must exist upstream of the catalyst. Research at NETL to develop a rich-quench-lean version of a trapped-vortex turbine combustor also depends on optimizing the mixing process in the quench zone.

To address the mixing issue, NETL is using two advanced diagnostics (acetone PLIF and 3-D PIV) to study a novel premixer concept. The premixer is a proprietary “hyper mixer” that may be useful to enhance the uniformity of compressor discharge flows, as well as enhanced fuel/air mixing. The work has been conducted under a CRADA with FloDesign, Inc. Air flow with non-uniform acetone concentration distribution was applied to the upstream of each mixing device, and PLIF images were taken downstream to examine the mixing enhancement by the device. Successful tests of this premixer are expected to help NETL propose additional work with catalytic combustor development and lead to commercial application of the FloDesign concept.

Clean Energy Systems: Concerns about climate change have encouraged significant interest in concepts for ultra-low or zero emissions power generation systems. In some proposed concepts, nitrogen is removed from the combustion air and replaced with another diluent, such as carbon dioxide or steam. In this way, formation of nitrogen oxides is prevented, and the exhaust stream can be separated into concentrated CO_2 and steam or water streams. The concentrated CO_2 stream could then serve as input to a CO_2 sequestration process. This project is an investigation of one approach to producing sequesterable CO_2 in a power production cycle.

In a power cycle proposed by Clean Energy Systems, Inc. Oxy-fuel combustion is used with steam as diluent. NETL is assisting with the development of a reheater for this application. The reheater is used to raise the steam temperature during turbine expansion to produce higher efficiencies than would be possible without reheat. The reheat combustion application is unusual. Most often, oxy-fuel combustion is carried out with the intent of producing very high temperatures for heat transfer to a product. In the reheat case, incoming steam is mixed with the oxygen and natural gas fuel to control the temperature of the output stream to about 1480 K. A potential concern is the possibility of quenching non-equilibrium levels of CO or unburned fuel in the mixing process. Inadequate residence times in the combustor and/or slow kinetics could possibly result in unacceptably high emissions. Thus, the reheat combustor design must balance the need for minimal excess oxygen with the need to oxidize the CO.

LONG TERM GOALS / RELATIONSHIP TO NETL's PRODUCT LINE(S):
This research supports the goals of both the High Efficiency Engines and Turbines and the Vision 21 Programs. Long term goals are to improve environmental performance (increased efficiency, lower CO_2, NO_X, and CO emissions), reduce costs (improved efficiency reliability, availability, and maintainability), and increase security (greater fuel flexibility) for gas-fired power systems.

RESEARCH OBJECTIVES, ACCOMPLISHMENTS AND RESULTS by Project:

COMBUSTION DYNAMICS:

Research Objectives:

Rijke Flame Stability Study

- Improve upon the design of the laboratory burner
- Evaluate the performance of the burner at different operating conditions
- Complete an acoustic model
- Develop an experimental method to determine flame surface area

Active/Passive Fuel Injector Development

- Develop an acoustic transfer matrix model for the fuel injector
- Construct two premixing fuel models with variable (not fixed) acoustics
- Develop an analytic model that shows how combustion phase can be modified by two acoustically active fuel injectors.

Rig-to-Engine Project

- Complete the development of this test method in the NETL pressurized Dynamic Gas Turbine Combustor Rig
- Publish results and pursue commercial interests

Summary Accomplishments:

Rijke Flame Stability Study

- Improved the flame anchor by incorporating a ring stabilizer at the mixture exit.
- Completed performance/stability map of ring-stabilized methane/air flame.
- Developed algorithms to evaluate the flame surface area from high-speed digital images.
- Made phase-gain comparisons of flame surface area variations with oscillating heat release rate. (Purely kinematic models could not predict the results, as previously believed.)
- Assembled an experimental system to perform planar laser induced fluorescence (PLIF) and particle image velocimetry (PIV).
- Papers presented at the Western Section of the Combustion Institute meetings.

Active/Passive Fuel Injector Development Accomplishments

- Developed an acoustic transfer matrix model for the fuel injector
- Constructed two premixing fuel models with variable (not fixed) acoustics
- Recorded data on the acoustic response of the variable acoustic premixer
- Developed an analytic model that shows how combustion phase can be modified by two acoustically active fuel injectors.

Rig-to-Engine Accomplishments

- Developed a simple analytic model to describe dynamic flame response.
- Published a joint technical paper at the ASME TurboExpo 2001 meeting.
- Investigated alternative (non-optical) techniques to measure dynamic flame response.

Results:

Rijke Flame Stability Study: This study examines the phase-gain relationship between flame surface area and heat release perturbations in dynamically unstable and externally excited flames. Natural chemiluminescent CH* emissions, used to define the flame surface, were captured by high-speed photography, and individual images were evaluated to form a signal representing surface area perturbations, Figure 1. Time-aligning this data with pressure and OH* chemiluminescent emissions (heat release indicators) permit investigation of the phase relationship between these parameters.

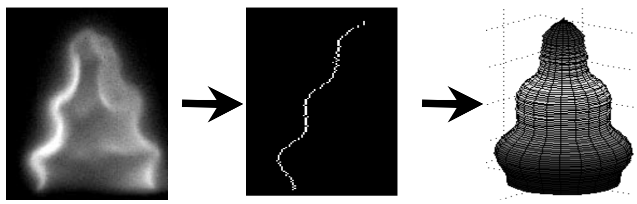


Figure 1: Representation of algorithm to determine the flame surface area from digital image of flame.

Results indicate that the flame becomes generally unstable when operated above $\phi = 0.7$, with the maximum instability occurring between ϕ=0.8-0.9. The flame becomes stable again for all cases at $\phi = 1.1$. Heat release (OH*) and flame surface area fluctuations were observed to be directly proportional to each other.

If variations in the heat release rate were solely dependent on the flame surface area, then these two parameters should be in phase with one another. For the small amplitude and excited flame cases (occurring at ϕ=0.7 and 1.1) the phase difference is essentially constant but non-zero. This phase lag may be due to chemical kinetics However, as the amplitude of the oscillations increase (approaching ϕ=0.9), the phase differences become more erratic, suggesting that other mechanisms may act to influence the heat release rate. Thus, flame models based solely on a kinematic relationship will not accurately predict the heat release phase, and control systems utilizing these models may actually increase or induce thermoacoustic instabilities. Additional mechanisms must be considered and studied under naturally unstable and excited conditions in order to include their effects in flame models.

<u>Active/Passive Fuel Injector Development:</u> This study analyzes the dynamic response of a premix fuel injector, where a variable geometry resonator is used to modify both the magnitude and phase of the fuel response. By changing the properties of the resonator, the proposed fuel injector can modify the phase of fuel fluctuations delivered to the combustor. Much like an active control system, the delivery of properly phased fuel pulses can enhance the stability of the combustor. The degree of stability enhancement depends on both the magnitude and phase of the fuel response that can be delivered by changing the geometry of the fuel resonator.

To determine the magnitude and phase of the fuel delivery, a model of the acoustic processes in a premix fuel injector was developed. Acoustic transfer matrices were used to relate acoustic pressure and mass flow at various points along the nozzle, and a dynamic model for the premixer orifice flow was developed from a linearized momentum balance. Experimental measurements show excellent agreement with predictions for the magnitude and phase response of the orifice model. The dynamic response with the variable geometry resonator is also studied, using both a representative impedance measured at the point of fuel entry and idealized cases of infinite and characteristic impedance at the same point. These cases bracket the expected range of realizable magnitude and phase response. Based on the representative impedance (measured), the range of phase that is achieved with the present variable-geometry resonator is approximately 70 degrees. The magnitude of the fuel fluctuations is appreciable compared to the average fuel flow. These results can be used in a feedback-loop model to determine if this response range is adequate to enhance stability in a given combustor. This approach was applied to an actual test combustor, and the measured response was in good agreement with predictions from the model, Figure 2. Ongoing studies will evaluate how a combination of variable geometry resonators, on both the fuel and air supply, can be used to enhance stability.

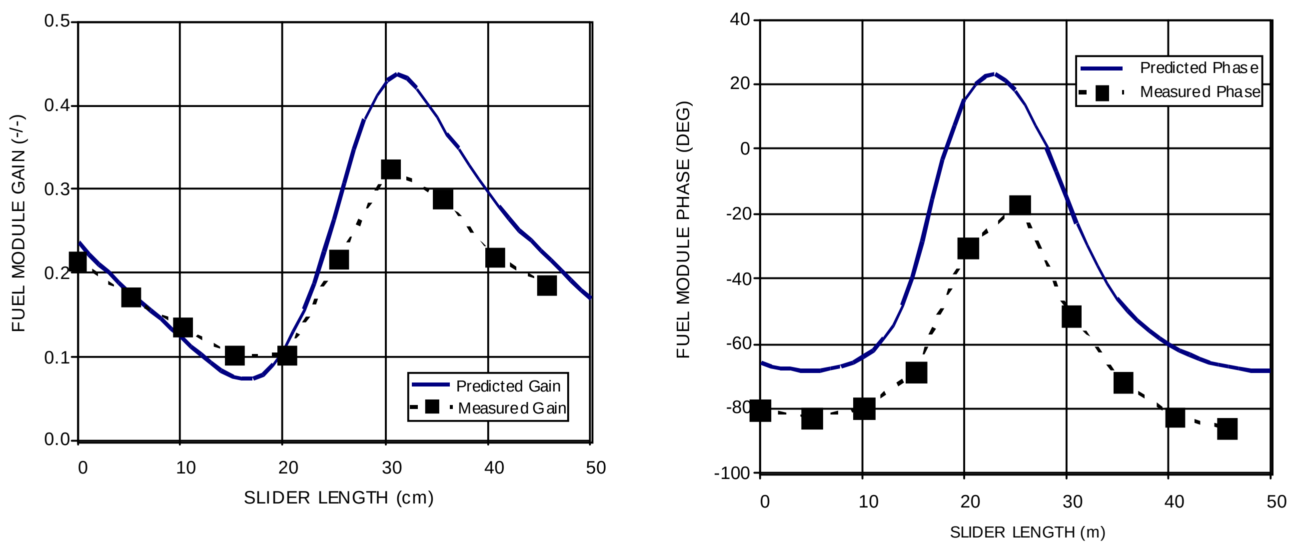
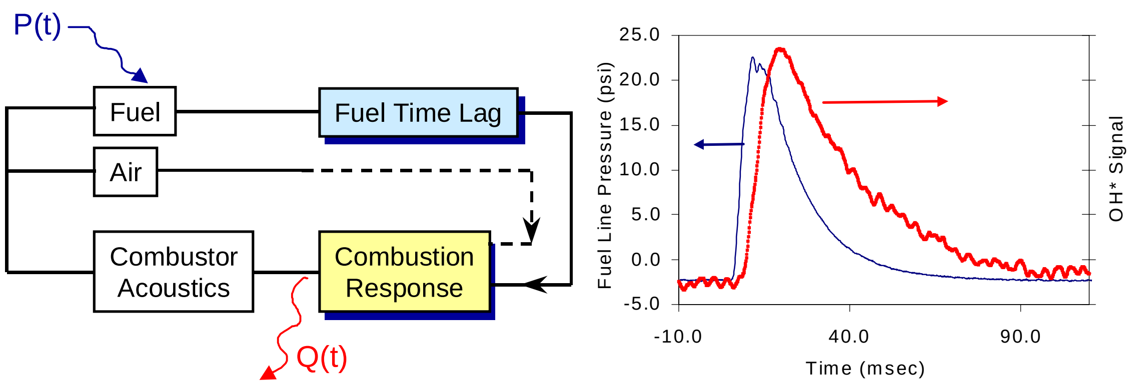


Figure 2: Comparison of measured gain and phase to model predictions for combustion tests.

Rig-to-Engine Project: To measure the dynamic response of a flame, small perturbations in the fuel flow are introduced into the system, Figure 3. Typically, it takes 1-10 milliseconds for a perturbation in fuel to cause a corresponding change in the flame. By measuring this time delay, key features of the dynamic system can be assessed. As part of an on-going collaboration between NETL and the Virginia Polytechnic Institute and State University, a simplified dynamic flame model was developed to complement the experimental data. By combining the experimental data with this simplified flame model, the fuel-transport time-scales can be separated from the combustion time-scales as a function of operating condition. More work needs to be done, however, to refine some of the assumptions in the model and improve the measurement uncertainties.

To simplify the anticipated commercial application of this approach, alternative methods of measuring the flame response are being considered. Particular interest has been given to techniques that do not require optical access into the high temperature region of the combustor. A patent has been filed for the technique, and the concept will not be discussed in any detail in this document.



(a) (b)

Figure 3: (a) Dynamic system with external fuel perturbations, P(t), and resulting flame response perturbations, Q(t). (b) Data from NETL's Dynamic Gas Turbine Combustor Rig.

<u>FLOW CHARACTERIZATION</u>:

Accomplishments:

Figure 4 shows the FloDesign lobed mixer used in the CRADA testing. The diameter of the last (flow exiting) stage is approximately 4 inches, and the overall length is approximately 4 inches. Mixing comparisons were made for three different mixing configurations to evaluate differences in the degree of mixeding. Configuration 1 used the lobed mixer, configuration 2 used a perforated plate mixer, and configuration 3 was a base case with no mixing enhancement. The degree of mixing was evaluated using Planar Laser Induced Fluorescence (PLIF). Acetone was seeded into the flow as a surrogate fuel and fluorescing medium. At an air stream velocity of 7 ft/sec (Reynolds Number = 19,100) the degree of mixing enhancement by perforated plate and lobed mixer were comparable. At higher air velocity (50 ft/sec), the lobed mixed produced a more uniform concentration distribution as compared to the perforated disk. While both devices generated small-scale vortices to enhance mixing, the lobed mixer favored stronger recirculation and more robust vortices for mixing. PLIF images indicated the mixing in the center core of the lobed mixer was ineffective. FloDesign concluded that this was

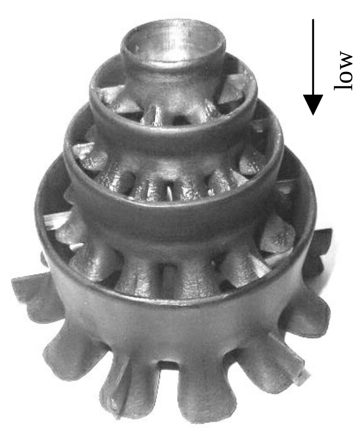


Figure 4. FloDesign Multi-Stage Hyper-Lobed Mixer

caused by the removal of an entrance stage, which will be reinstalled in their future design. The pressure loss experienced by the lobed mixer was found to be about 14% of the perforated disk.

CLEAN ENERGY SYSTEMS:

Research Objectives Reheat combustor design requirements, shown in Figure 5, are similar to turbine combustion, but have a key distinction: to reduce the requirement for pure oxygen, combustion must be carried out with minimal excess oxygen and with steam diluent, rather than nitrogen. No prior combustor development has considered these unique requirements, and few facilities have the pressurized oxygen and steam flows needed to verify the performance of proposed reheater designs. Thus, the goal of the present research is to propose a reheater design to meet the operating requirements shown on Figure 1 and perform a proof-of –concept test of the resulting design.

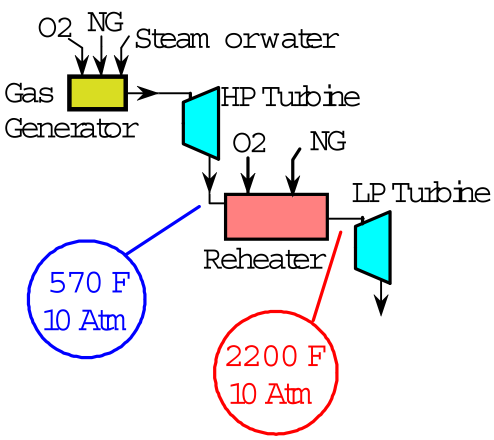


Figure 5. Power cycle schematic.

Summary Accomplishments

- Established combustion operating requirements over the planned load range for the CES design.
- Proposed a reheat combustor design and test program that was acceptable to CES.
- Completed zero-and one-dimensional model studies of combustor residence times for steam and CO2 diluents.
- Prepared a paper on zero and one-dimensional model results for the American Flame Research Committee International Symposium.
- Prepared an invited lecture on oxy-fuel combustors for zero-emission power plants at the Zero Emission Steam Workshop, Aug. 28-29, 2001, in San Francisco.
- Evaluated potential test locations and selected and procured test service arrangements at NASA Glenn Research Center, Plumb Brook Station.
- Completed detailed 3-D CFD simulations of the reheat combustor design.
- Began detailed combustor design for fabrication and testing in FY2002.

RESULTS: The initial design was developed using zero and one-dimensional model studies to size the combustor components. These studies were needed because of the unique chemical reaction rates associated with dilute oxy-fuel combustion. A stirred reactor model of the combustor primary zone was developed using the CHEMKIN solver [1] with kinetic rates from GRI Mech 3.1 [2]. Trade-offs between the normalized fuel air ratio (Φ), the residence time, and the amount of steam diluent (H20/O2 ratio) were evaluated relative to equilibrium combustion products. Optimal primary-zone diluent levels produced a minimum of carbon monoxide in the primary zone. Lower CO levels existed for longer residence times and with excess oxygen (Φ=0.9). These results were used to establish the basic combustor dimensions and flow rates.

Once the basic combustor dimensions and diluent levels were established, detailed mixing strategies were proposed and tested numerically using the FLUENT code. Figure 6 shows a temperature prediction of the proposed combustor design. Colors represent the temperature field. Flow is from left to right. The center of the combustor is essentially a uniform temperature, indicating complete fuel oxidation before final diluent addition (note the final diluent flow entering the conic neck-down at the right). Detailed mechanical designs of the combustor are now being developed. Tests of the combustor assembly will be carried out at NASA Glenn's Plumb Brook Research Station, which is equipped with the required oxygen and steam supplies.

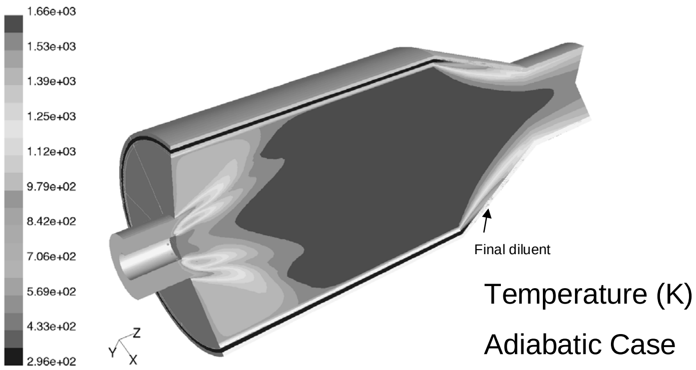


Figure 6. Simulation of the combustor design using the FLUENT code.

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SENSORS FOR TURBINES:

Research Objectoves: Provide robust low-cost solutions for in-situ monitoring of combustion parameters to achieve sustained low-emission operations, finely tuned control, and in-situ diagnostics of the combustion process.

Summary Accomplishments:

- A method to measure flame flashback and potentially measure the local fuel-air ratio have been tested, showing encouraging results.
- A literature review of flame ionization has been conducted to support analysis of flame ionization measurements.
- A paper on the flame flashback detector has been presented at the American Flame Research Committee Meeting. This paper outlines the flashback detection technique.

- A paper on the in-situ monitoring potential of the flashback detector has been presented at the Western States Combustion Institute Meeting.
- A task at University of Pittsburgh was completed (through the NETL site-support contract) to measure the electrical properties of thermal barrier coatings (TBC's).
- A task was started with West Virginia University (through the NETL site-support contract) to measure flame impedance in the flat flame burner at NETL.
- Performed testing of the flashback/in-situ monitoring technique in the NETL Dynamic Gas Turbine Combustor
- Patents were filed on both the Flashback Detection Sensor (FDS) technique and the Combustion Control and Diagnostics Sensor (CCADS) technique.

RESULTS: The sensing technique developed at NETL uses a preferred sensor embodiment that is integrated on the premixing fuel injector center-body at the point of flame anchor. An equal-potential voltage is applied to the two electrically isolated electrodes to create an electric field across the flame, and the current through the flame is measured using a simple two-wire technique. The two-electrode configuration facilitates both diagnostics (e.g., incipient flashback & auto-ignition detection) and in-situ monitoring of the local combustion process. Results obtained in the NETL Low Pressure Development Combustor (LPDC) show a high potential for both diagnostics and in-situ monitoring using the CCADS technique. The LPDC configuration for testing the flashback detection capability of the sensor [6] is illustrated in Figure 7. Test results indicate that the dynamic response of the CCADS technique is sufficient to capture incipient flashback events during dynamic pressure oscillations. These tests also indicate the importance of having a two-electrode arrangement for detecting flashback with a guard (G) electrode located at the end of the center-body to prevent current flow through the sense [6] electrode until the flame is inside the fuel injector.

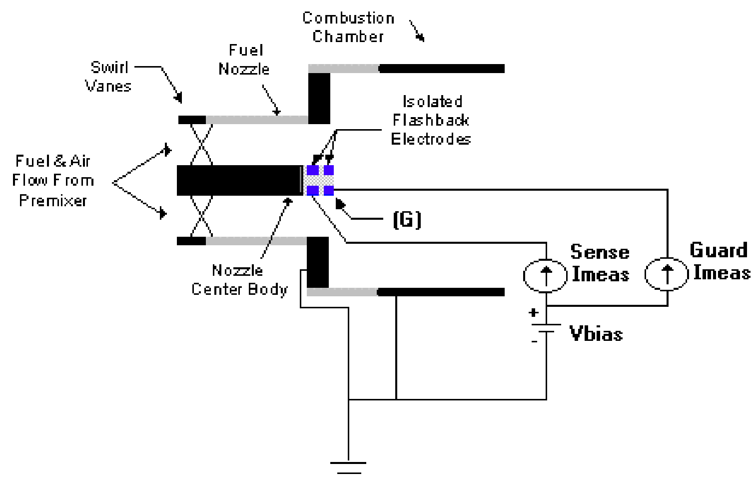

Figure 7: LPDC Configuration with CCADS electrodes, and two independent direct current (DC) measurement circuits.

Current measurement through the guard electrode can potentially be used for in-situ monitoring of combustion parameters. Testing in the LPDC using the configuration shown in Figure 8 indicates a high potential for the in-situ monitoring capability of the CCADS technique. Two isolated 1/4-in. (316 stainless steel tubes with ceramic inserts) electrodes were installed 180° apart inside the cylindrical, quartz, combustion tube [7]. The two electrodes were electrically isolated from the remaining conductive combustor surfaces and were connected to the current measurement circuit, thus constraining the electric field between the guard electrode (G) and the two electrodes (E) in the combustion zone. The data in Figure 5 show the measured current versus the applied voltage at a constant bulk flow rate of fuel and air, where the relationship is linear over a range of operating equivalence ratios. This is much like the response of a flame ionization detector, where changes in hydrocarbon concentration at a constant bulk flow velocity yields a change in current. The data in Figure 5 also show that an increase in equivalence ratio (i.e., an increase in hydrocarbon concentration) indeed produces more current through the flame, and the current has a linear relationship to the operating equivalence ratio of the combustor. Other experiments were conducted using chemiluminescence sensor techniques, and the results compared well with the current measurements over a range of operating equivalence ratios [7]. This indicates that the measured current through the flame relates to the operating equivalence ratio of the combustor.

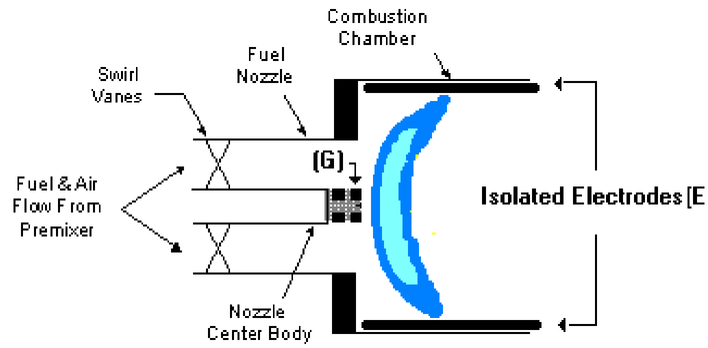

Figure 8: LPDC configured with CCADS electrodes on fuel injector center-body, and two electrically isolated electrodes (E) in the combustion chamber.

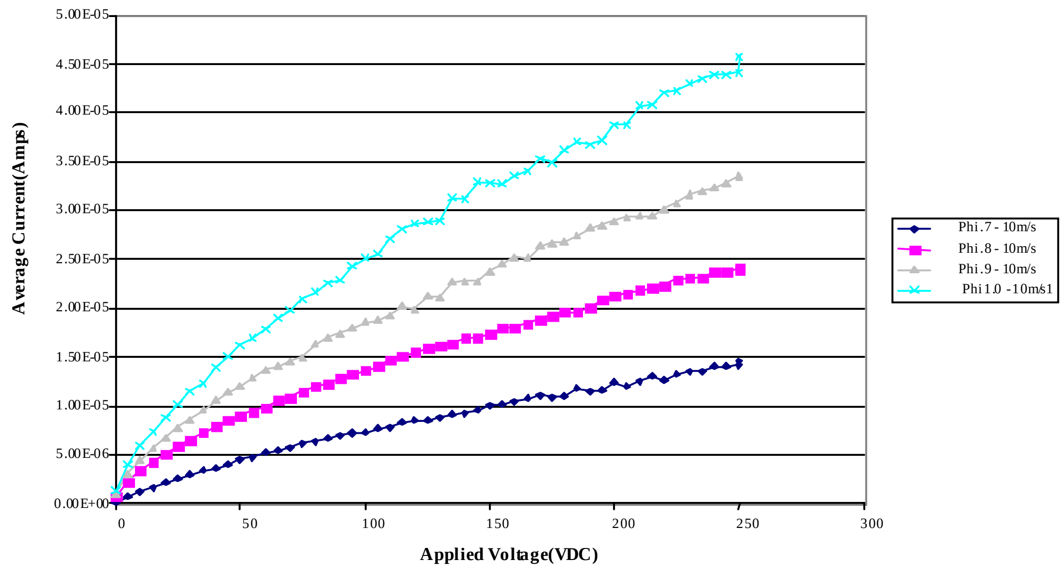

Figure 5. Shows the average current measurements over a range of applied voltages (Vbias) and equivalence ratios (Phi 0.7-1.0), at 10 m/s bulk flow velocity.

Additional investigations of the CCADS technique at turbine operating conditions are ongoing in NETL's high-pressure combustion facility. In addition, low-pressure experiments and detailed simulations are planned for FY02 to further understand the physical relationship between the operating parameters of combustion and the measured current through the flame.

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